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Geometric Reconstruction of 3-D Objects from Digital Images

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Abstract

This paper is an over-view of on-going research and development at the department of geodesy and photogrammetry of the Royal Institute of Technology in Stockholm within the field of automatic reconstruction of the geometry of 3-D objects from digital images. Two on-going research projects will be described. The first is experiments with line photogrammetry from digital images to find out what geometric accuracy will be attained when all edgels in all images are used together with geometric contraints in a simultaneous least squares adjustment of a group of straight lines describing a house. The second is research about generic descriptions of buildings as a basis for segmentation of images into lines and regions which are interpreted (parsed) as an object in 3-D space.

Historical background

When I now will introduce the subject I have chosen to give a historical background from a very personal perspective.

25 years ago I left the Royal Institute of Technology with my doctoral degree in my pocket and I began to work with a private company as a consultant. Among other things I produced digital elevation models with field surveying and photogrammetry. The models were used in technical design of civil engineering works, such as road construction, housing, volume calculations of gravel pits, etc. Computers were used for cut and fill calculations of earth masses in road design, and for checking the volumes taken out from gravel pits (Torlegård 1972). But it could happen that some engineers wanted to have the DEM as numbers written in a grid pattern on a sheet of paper.

In 1980 - 84 when I had been professor alreday several years, I chaired an ISPRS WG on mathematical aspects of digital elevation models. The WG organised a controlled experiment where the participants used their own methods to produce digital elevations models of 4 to 6 different terrain types. We at the department measured the same terrain from low altitude photographs and used that as "ground truth" in an assessment of the quality of the DEMs made by the participants (Torlegård, 1981,1983, 1984, 1986). We learnt a lot from this activity, including how difficult it is to design and pursue a research project with many counterparts whose methods have parameters or degrees of freedom which are not under your control. One of my students was able to use some of the gained experience in his doctoral thesis on quality control and accuracy estimation of DEMs (Östman 1986).

By this time least squares matching for parallax determination had been demonstrated, and when another of my students wanted to have a subject for his thesis, I suggested him to develop least squares matching, because my experience told me that automation of the measurement of masses of points for DEMs would mean a big step forward for photogrammetry, as no stereo operator likes to sit in his instrument day after day just measuring spot heights or tracing profiles for DEMs. The result was the multi-point matching method (Rosenholm, 1987).

The next PhD student improved the method even further and introduced image hierarchies in the matching, and also detection of breaklines in the matching process (Li, 1989). By this time commercial products for digital photogrammetry were already on the market. Today there are several vendors of equipment and software for digitization of aerial photographs, for automatic inner, relative and absolute orientation, for automatic aerial triangulation, for parallax matching in digital elevation modelling, surface reconstruction and deformation measurement, and for orthophoto resampling and mosaicing. So what would be the next field for photogrammetric research?

What comes next in importance of the photogrammetric process? Again with my personal experience two decades earlier, I suggested to my co-laborators to try to automate the photogrammetric extraction of detail and information to be stored in urban data bases, i.e. the objects which traditionally are plotted on large scale maps for the city architect, the city surveyor and the city civil engineer. There are two phases of this automation, first you have the precise measurement of the photogrammetric features leading to the geometric description of the object. Then you have the more difficult task which is to select the image detail to be used for the geometric modelling in 3-D of the object which is to be measured.

Objective and Rationale

The objective of the current research in digital photogrammetry at our department is to find a theoretical sound basis for the automation of large scale photogrammetric mapping, or rather
automation of photogrammetric data acquisition for urban resources information systems and for urban databases.

Another formulation of the objective would be to say that the result of the research should contribute to photogrammetric processes which relieve the human stereo operator from the precise measurement of detail, in this case of man-made objects, such as houses, bridges, walls, kerb-stones, lamp poles.

The geometry of man-made objects can in most of the cases be described by a set of straight lines. To measure such objects is a task which is better suited for line photogrammetry than for point photogrammetry. This is true both for analytical and digital line photogrammetry. Line photogrammetry has a particular importance for the automation of digital photogrammetry as image operators work on one image at a time.

The basic elementary measurement task is to estimate the position in object space of a straight line from image edgels thereof in two or more images.

Another way of describing buildings is to apply generic modelling based on elements of a building such as roof, wall, corner, ground, etc., their geometry, their relations, and knowledge about how they form regions and lines in images of known geometry.

Research in this field can ultimately end up in methods where the operator selects an area in one image, an area in which there is a building. The computer then finds the corresponding areas in the other images, performs the goal oriented segmentation, and all the necessary analysis to find out what type of a building there is and what its geometry, position and shape are.

The string approach

Line photogrammetry

Already line photogrammetry based on lines observed by an human operator in several images is an improvement of accuracy compared to traditional stereo photogrammetry, mainly because more than two images are used. The position of the line in object space is calculated in a simultaneous adjustment of all observations in all images of a particular line. It is further possible to include in the adjustment also constraints so as to obtain a horizontal or a vertical line. It is also possible to constrain lines to each other, such as parallelity, perpendicularity, and intersection. (See for instance Mulawa and Mikhail 1988, Heikkilä 1991, Zielinski 1992).

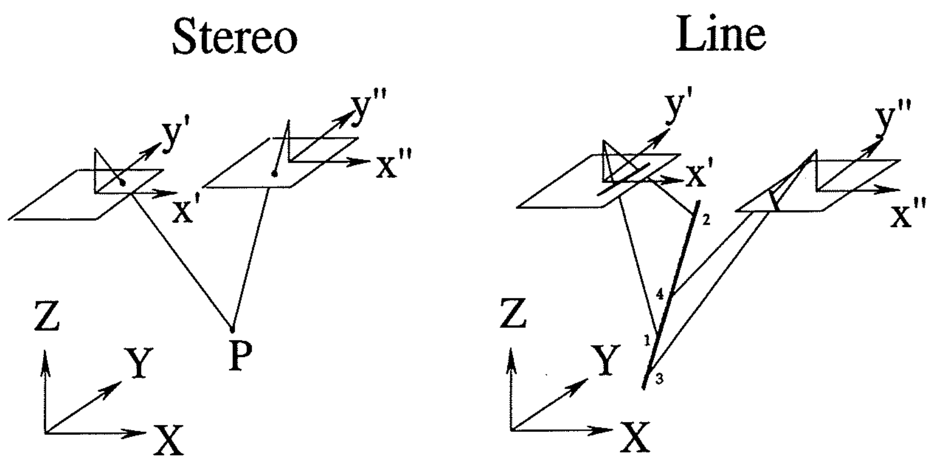


Fig. 1. One difference between stereo and line photogrammetry is that it it is not necessary to measure homologuous points in two ore more images. From Zielinski 1992.

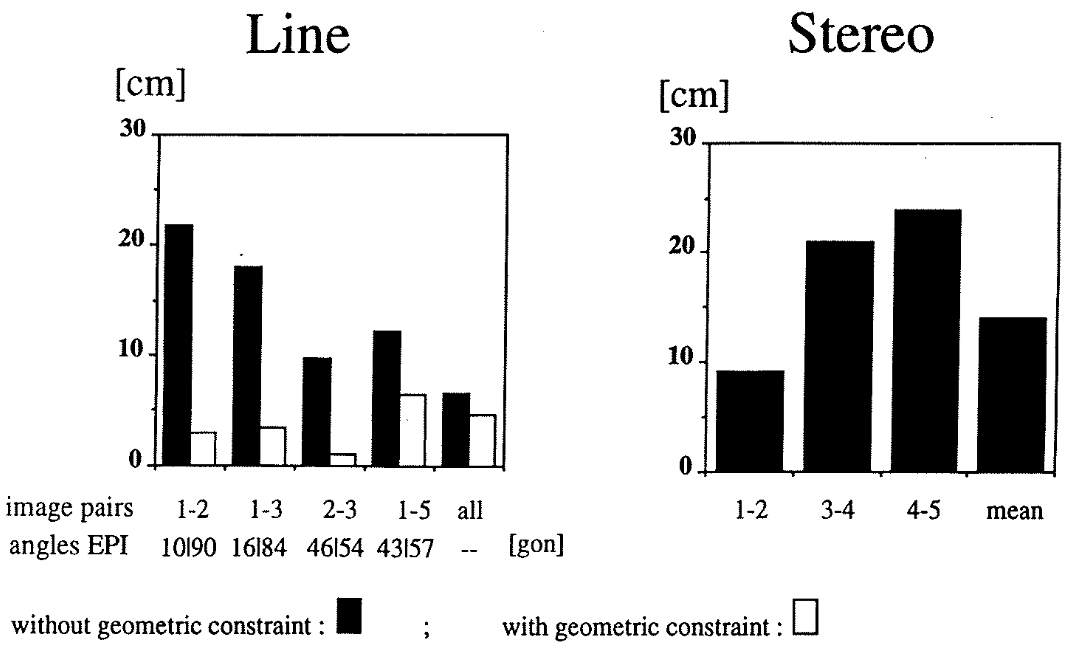


Fig. 2. Comparison of standard deviations of horizontal distances on a building with traditional stereo and line photogrammetry. From Zielinski 1992.

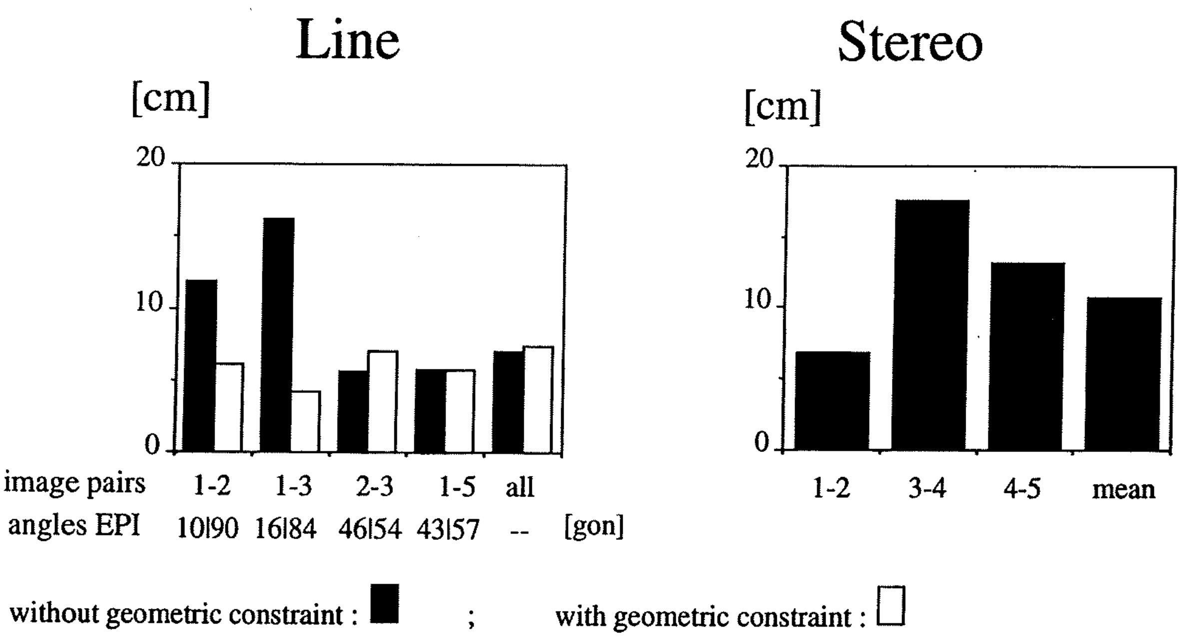


Fig. 3. Comparison of standard deviations of height differences on a building with traditional stereo and line photogrammetry. From Zielinski 1992.

Digital lines

The next goal is the automatic measurement of lines in the images, i.e. the use of edgels as observations rather than the measurements made by a human operator. In doing so we can increase the number of observations per image line from very few (2 - 4) made by the operator, to all the edgels which describe the lines. Assume a line in object space 10 m long imaged at scale 1:10 000 and digitized with 12.5 µm pixels. That yields some 80 edgel observations in each image. The edgels can also be given weights according to the precision of the edgels, estimated as contrast or something that describes the sharpness of the edgel. There is apparently a huge potential for increasing the accuracy by going digital, merely because of the increase of number of observations.

Edge detection

Before we can make these adjustment calculations we have to solve the problem of finding the edgels of interest for our particular task. We can of course apply traditional edge detection filters such as Laplace, Sobel, Förstner's interest operator, Dreschler, but that would give us too many edges, of which we have no interest. What we have done so far, is to segment the images so as to find the edges of interest. The result is fairly good, but there are still a number of edges which do not belong to our object to be measured. For the time being we manually select the line segments to be used in a simultaneous adjustment of the 3-D object geometry.

The segmentation of images to get the lines of interest is up to now done under interactive control by a human operator.The segmentation is a process that makes use of such methods as edge focusing (Bergholm, 1989), line growing (Förstner, 1991), polygon approximation (Bengtsson et al, 1986), and minimum description length (Axelsson, 1993). See Fig. 4.

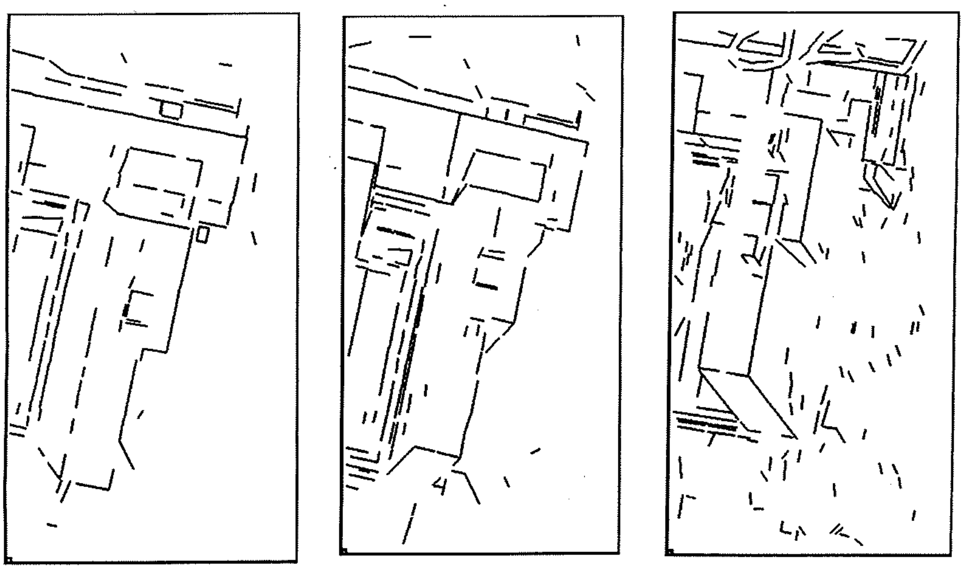
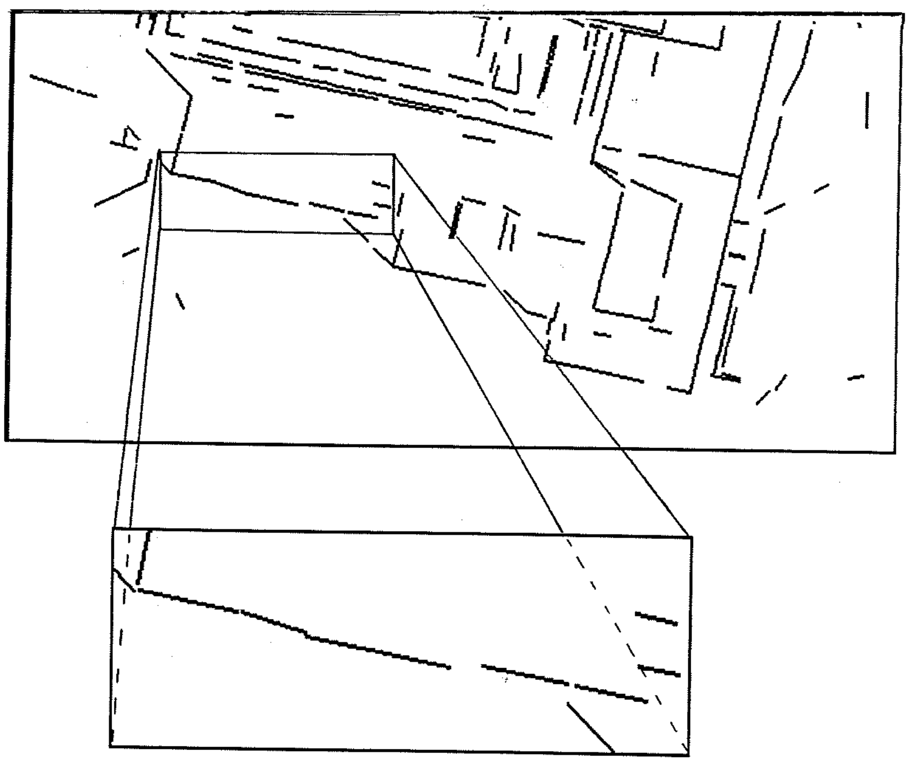


Fig. 4. Segementation of three aerial photographs of the same building. It is not an easy task to match the homologuous lines,

Minimum Description Length

The minimum description length (MDL) criterion is primarily a tool for comparing different data models. It solves the problem of comparing models of varying complexity and structure by extending the maximum likelyhood principle by including a term for the model complexity. This makes it possible to include geometrical constraints, e.g. perpendicularity, in the comparisons. The MDL criterion also can be used for making the process more robust against out-liers and false solutions (Axelsson, 1993). MDL can be used in 2-D as well as in 3-D.

Axelsson (1993) has shown examples from interpretation of 2-D data points using different models such as as a T-junction, an L-corner or straight line of fixed or arbitrary length. The data points are results of an edge segmentation of an image of a house. The MDL has also been used as a step in the automation of digital line photogrammetry adjustments. After segmentation of an image of a house, we often get several line elements which all belong to the object structure, e.g. a roof edge is often interupted by trees or shadows or other image noise. MDL can find out which of the segmented straight line elements are parts of one and the same straight line.



Number of line segments: 5

Number of points 276

Model	Model point	Outliers	% outlier	σ_m	MDL
Unmodelled	(276)				5134
Line segment	172	102	37 %	10 μm	4391

Fig. 5. Merging line segments with minimum description length MDL criterion. From Axelsson 1993.

Matching

The next step in automation is the matching of homologuous lines from different images. When this has been automated we have again relieved the human operator of a tedious task. As soon as he has identified and perhaps labeled a number of lines in one image, he has more or less finished the interpretation. To do the same again in all the other images, is mere repetition. So, to automate this would improve the situation for the operator. There are many ways in which this can be done. Many ideas have been presented in the literature, but no method is yet operational for photogrammetric applications. Here we have reached the research frontier. Methods use scale space theory (Bergholm, 1989), hierarchical image pyramids (Hannah, 1988), relational matching (Zilberstein, 1992), etc.

The generic approach

3-D Modelling

A different strategy is to not at all deal with matching of homologuous lines in images, but instead turn directly to the modelling of the object geometry in 3-D space. The difference in approach can be described as follows. In the line matching case we match lines, calculate their object positions, and then we combine them into a string model of the object. In the object modelling case the matching is guided by generic rules of relations between lines and surfaces comprising the 3-D object. Before this can be done, the images have to be segmented and interpreted (parsed) to find surfaces and their boundaries to be used in the modelling.

A Knowledge based Approach

This modelling of a 3-D object is based not only on the geometry of regions and lines or edges found in images, but also on rules how to interprete them and on strategic process control. This division of knowledge in facts, rules and strategy is used in many commercial available softwares for knowledge based system shells, and the modelling can later make use of such software. The knowledge is of course related to a particular type of object. In our case we have selected the object house or building for our research. It is complicated enough, and it is a very frequent object for photogrammetric mensuration (see Gülch 1992 and Stokes 1992).

Parsing

The general strategy of the modelling is first to segment all the images containing the object, then to interpret these images. This interpretation has two parts, the parsing of each image and a consistency check of the separate parses. The strategy is not to develop a parsing that can cope with all cases, but rather to try several parsers until an acceptable consistency is obtained. The parsing alternates between line segments and region segments. The rules describe geometry of and relations between walls, roof, ground, door, window, chimney, etc. The parsing of the images is using the generic modelling of perspective projection of a house on an image plane (Stokes, 1992). See Fig. 6. The parsing has been tested on perspective line drawings of a house which are synthetic segmentations without noise, i.e. error-free lines and regions. These simulated images feature a house that is rather complex. The result of the test is however very promising for the future, but the problem is the segmentation which has to be done before the parsing (Gülch, 1992).

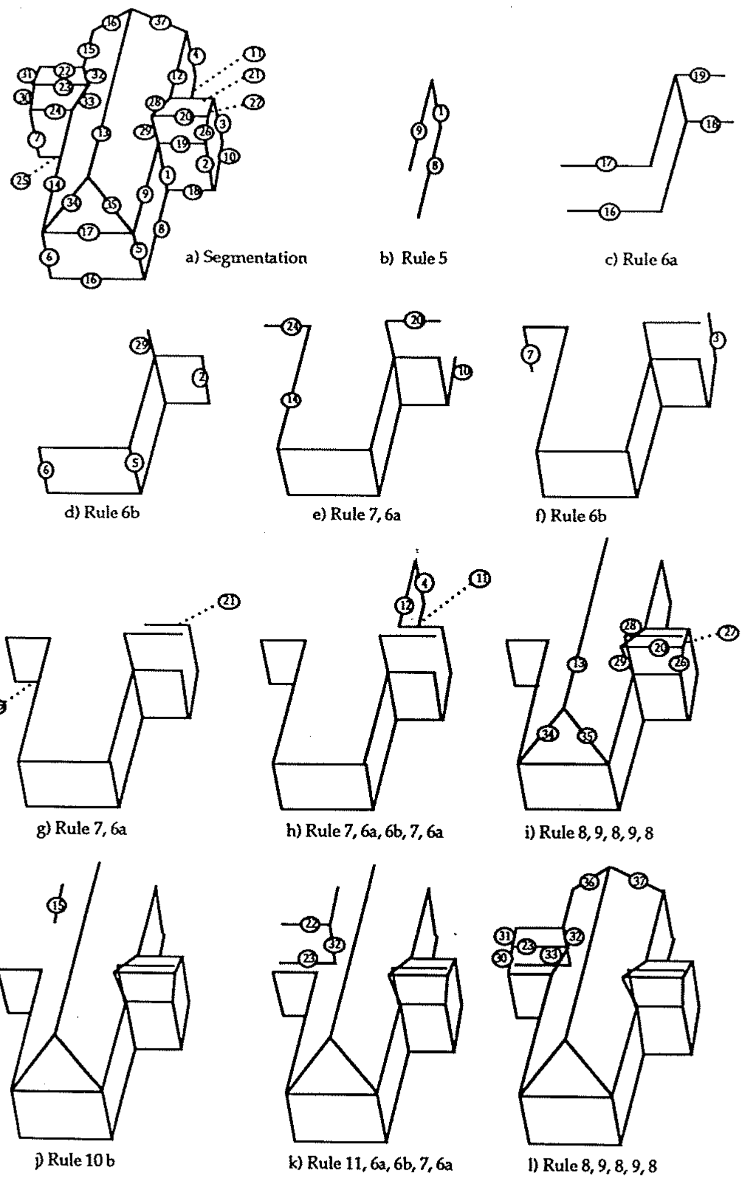


Fig. 6. Application of rules for the parsing of a segmentation (a line image) of a building. From Stokes 1992.

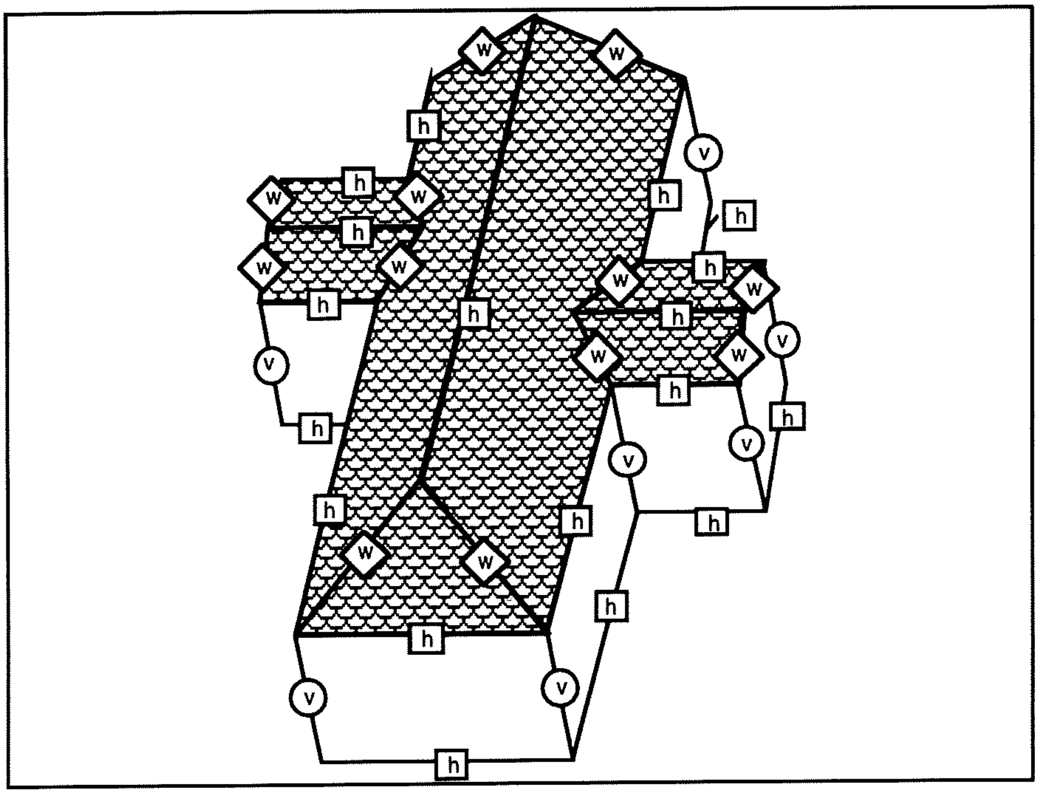


Fig. 7. Final result after consistency check using several segmentations of the same building. Lines and building parts in object space are correctly found.

Segmentation

It is evident from our experience that the requirements on the result of the segmentation is very demanding. Even if we use combinations of rather advanced segmentation procedures, the result is not directly suited for parsing. Presently we are developing algorithms and programming our computers for our own ideas about how to segment images for the 3-D modelling of houses. Preliminary results are expected this coming summer.

International Cooperation

The ISPRS has established a WG III/2 on Geometric-Radiometric Models and Object Reconstruction which deals with the above problem. Its terms of reference are:

> Object reconstruction is that combination of image processing, pattern recognition and artificial intelligence technologies which focuses on the computer analysis of one or more digital images with the aim of determining position and shape of the objects of interest. The reconstruction process often uses geometric and radiometric modelling and complex knowledge representations in an expectation or model based matching or searching methodology. In object reconstruction no explicit modelling of the semantics of the extracted objects is amed at , though possible.

This working group deals with such topics as
- geometric and radiometric image formation

- reconstruction of image orientation and of object points, lines and surfaces
- perceptual grouping
- geometric reasoning
- image transformations, and
- image and surface segmentation.

The working group will report to the ISPRS Commission III symposium to be held in Munich Sept 5-9, 1994, and to the 18th ISPRS Congress to be held in Vienna July 9-19, 1996. Persons and institutions having an interest in the field are welcome to join the working group. Please contact E. Gülch at our department.

Future research

The research reported here is on-going just now at the department of geodesy and photogrammetry. It is aiming at more automated methods in digital photogrammetrry. Reconstruction of inner, relative and absolute orientation of images in pairs and in blocks can be done automatically with digital methods. The geometric modelling of the shape of nice surfaces like the terrain or industrial products is more or less solved already. Recontruction of such surfaces can be done automatically when some general requirements are fulfilled.

The reconstruction of the geometry of 3-D objects from digital images is the next photogrammetriuc task to be automated. The two approaches with string models and generic models have both been studied at the department. Applications for future funding have been based on both approaches. We hope to be able to continue with both and we will be very disappointed if we don't get funds for any of them.

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